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PROGRESS TOWARDS LASER PLASMA ELECTRON BASED FREE ELECTRON LASER ON COXINEL

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Abstract

Laser plasma acceleration (LPA) [1] with up to several GeV beam in very short distance appears very promising. The Free Electron Laser (FEL), though very challenging, can be viewed as a qualifying application of these new emerging LPAs. The energy spread and divergence, larger than from conventional accelerators used for FEL, have to be manipulated to answer the FEL requirements. On the test COXINEL experiment [2–4] line, "QUAPEVA" permanent magnet quadrupoles of variable strength [5, 6] handle the emittance growth and a decompression chicane reduces the slice energy spread, enabling FEL amplification for baseline reference parameters [2]. A beam pointing alignment compensation method enables to properly transport the electrons along the line, with independent adjustments of position and dispersion [7]. The measured undulator spontaneous emission radiated exhibits the typical undulator radiation pattern, and usual features (gap tunability, small linewidth...).

INTRODUCTION

Accelerator based light sources presently know a very wide development [8], with the FEL [9] advent in the X-ray domain [10] coming along with an increase of the peak brightness by several orders of magnitude, enabling fifty years after the laser invention [11] to decipher the matter structure in unexplored areas and dynamics on ultra-fast time scales unraveling the processes involved various domains [12]... Following the laser invention, alternately of developing FELs relying on non bounded relativistic electrons in an undulator periodic permanent magnetic field as a gain medium [9], laser have been considered to generate and accelerate electrons in plasmas [1]. An intense laser focused onto a gas target ionizes the gas and creates a plasma. As the laser pulse propagates, the ponderomotive force expels electrons from the optical axis, forming a cavity free of electrons in the laser wake with large amplitude electric fields where electrons can be trapped and accelerated. With the growth of ultra high power laser making advantage of Chirped Pulse Amplification techniques [13], electrons can be accelerated with plasma up to several GeV within ultra-short distances [14–16] with kA peak current, ultra-short bunches, 1π mm.mrad normalized emittance beams, enabling to consider LPA to drive an FEL [3, 17]. Even though some LPA features such as peak current and emittance seem to be quite suitable for the FEL application, energy spread and divergence do not meet conventional accelerator µrad divergence and per mille of energy spread beams. They should be handled to mitigate chromatic effects [18, 19], that can lead to a dramatic emittance growth and afferent beam quality degradation in the transfer lines. Large divergence requires strong focusing right after the electron source, with for instance high gradient permanent magnet quadrupoles [20]. Large energy spread can be managed by a decompression chicane [3, 21] or a transverse gradient undulator [22, 23]. The energy-position correlation introduced by the chicane [2] can be turned into an advantage. There are still very few experiments with LPA electron beam transport towards an undulator [24] and preliminary observation of undulator radiation [25–28]. The COXINEL program [29] aiming at demonstrating FEL amplification using a dedicated manipulation line is developed in the frame of the LUNEX5 project of advanced compact free electron laser demonstrator [30, 31]. We report here the progress on the COXINEL experimental program.

THE COXINEL LINE DESIGN

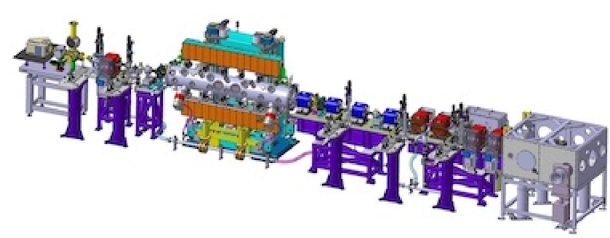

Figure 1: COXINEL line CATIA sketch.

The COXINEL line (see Fig. 1) has been designed and built at Synchrotron SOLEIL [4, 32] (ERC Advanced COXINEL 340015) using the baseline reference parameters given in Table 1 for the 180 MeV case, for being installed at Labora-

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toire d'Optique Appliquée (LOA). The divergence is rapidly mitigated (5 cm away from the source) via strong focusing with a triplet of QUAPEVA permanent magnet based quadrupoles of variable strength (with rotating cylindrical magnet surrounding a central Halbach ring quadrupole [33]) and adjustable magnetic center position (with translation tables) [5,6]. A magnetic chicane then longitudinally stretches the beam, sorts electrons in energy and selects the energy range of interest via a removable and adjustable slit mounted in the middle of the chicane. A second set of quadrupoles matches the beam inside an in-vacuum undulator. Electron diagnostics include current transformers, cavity beam position monitors and removable scintillator screens for electron profile imaging [34]. The "200 MeV" corresponds to radiation in the UV with a 2 m long cryo-ready undulator U18 (period 18 mm) [35], while the 400 MeV case associated to the U15 cryogenic undulator enables to reach the VUV spectral range. The line equipments have been characterized [4, 32].

The electron transport [36] images the electron source in the undulator. The total emittance growth is frozen at the QUAPEVA triplet exit. The "supermatching optics" focuses each electron beam slice in synchronisation with the progression of the amplified synchrotron radiation along the undulator, taking advantage of the energy - position correlation introduced in the chicane, and enables to achieve FEL amplification with the baseline reference parameters [2]. The sensitivity study of the FEL versus different parameters has been carried out [37]. Other optics (focusing on the screens for transport tuning, focusing vertically in the chicane equipped to select the energy of interest with a slit) are also available.

Table 1: COXINEL baseline reference case at the source and undulator (Und.), measured (Meas.) beam at the source.

Parameter (unit)	Baseline Source	Und.	Meas. Source
Vert. divergence (mrad)	1	0.1	1.2-5
Hor. divergence (mrad)	1	0.1	1.8-7.5
Beam size (µm)	1	50	
Bunch length (fs RMS)	3.3	33	
Charge (pC)	34	34	
Charge density (pC/MeV)	5	0.5	0.2-0.5
Peak Current (kA)	4.4	0.44	
Energy spread RMS %	1	0.1	>10
Norm. emittance ϵ_N (mm.mrad)	1	1.7	

COXINEL MEASUREMENTS

LPA is operated in ionisation injection [38] for robustness with the LOA 1.5 J, 30 FWHM fs pulse laser is focused into a supersonic jet of $He - N_2$ gas mixture. Electron energy distribution (see Fig. 2 (left)) is broad and ranges up to 250 MeV, with a much lower charge density at the energy of interest and larger divergences than expected (see Table 1).

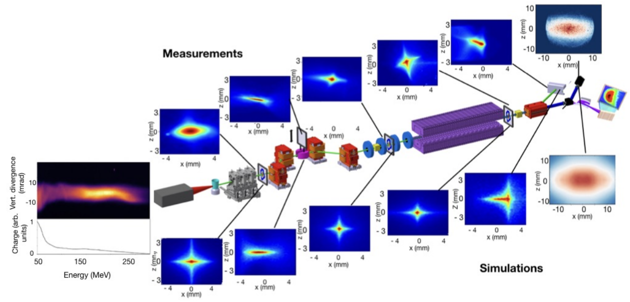

Figure 2: COXINEL electron and photon beam measurements compared to simulations using measured electron beam distribution as an input. Left : electron beam spectrometer measurements and transverse distributions along the line. Right : undulator radiation transverse pattern.

Besides prior alignment of the line components within ± 100 µm on the same axis with a laser tracker, and optics daily alignment with a green reference laser, the LPA electron beam pointing (of the order of 1.5 mrad RMS) makes critical the electron beam transport along the line. Thus, a matrix response beam pointing alignment compensation method taking advantage of the "QUAPEVA" adjustable magnetic center and gradient is applied : the electron position and dispersion are independently adjusted [7] step by step along the screens enabling a proper transport along the line. The QUAPEVA strength is slightly adjusted to optimize the focusing thanks to the rotation of the QUAPEVA cylindrical magnets. The matched transported beam measurements are well reproduced with simulations for measured beam characteristics (see Fig. 2), with cross-like shaped focused beam due to chromatic effects and measured tilted beams due to skew quadrupolar terms, that have been further corrected [39].

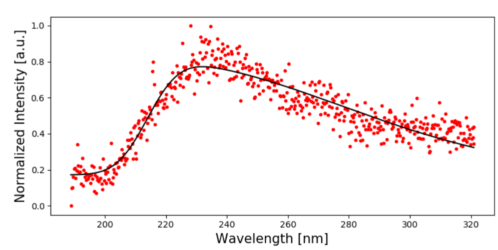

Figure 3: Undulator spectral flux measured with the Horiba iHR 320 spectrometer at 5 mm gap (3 mm electron slit).

The radiation from the 2 m long 107 x 18.16 mm periods U18 is then characterized while applying an optics enabling to select a small energy range centered onto the energy of interest with the slit inserted in the magnetic chicane. A typical spectrum is presented Fig. 3, and 2D measured and simulated transverse patterns are displayed in Fig. 2. The undulator radiation (resonant wavelength, intensity) has been tuned by changing the gap. The radiation linewidth can be

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controlled using the electron beam energy selection via the slit in the chicane. The estimated full number of photons per beam charge N_{ph} is $\approx 3.10^7$ pC^{-1}.

CONCLUSION

We have demonstrated a proper LPA electron beam transport on COXINEL, handling its performance for a FEL application. We have then observed at the end of the line undulator radiation exhibiting the usual characteristics in terms of spatio-spectral distribution, wavelength dependance with gap, spectral purity. The observation of an FEL effect seems possible, provided electron beam measured parameters get closer to the baseline reference case ones [40].

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